Building an Information Fusion Demonstrator

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Abstract - *The paper describes an ongoing effort to build a demonstrator system where new ideas in information fusion may be tested and demonstrated. The motives behind this project, its system architecture and development process, and some of the fusion methods being developed for the system are briefly described.*

Keywords: Scenario simulation, force aggregation, tracking, resource management.

1 Introduction

Information fusion research basically deals with the creation, analysis, and evaluation of methods for interpreting observational data in the context of complex models of reality, describing possible alternative future developments and evaluating their likelihood. In the defence application area, this research develops fusion processes which exploit a dynamic target situation picture produced by multisensor fusion by combining its information with relevant a priori information, in order to refine and interpret a battlespace situation picture. Ultimately, this semi-automatic intelligence interpretation process aims at delivering a comprehensive picture of the opponent´s options and, based on an evaluation of these options, suggest his likely intentions.

In ground-based scenarios, the a priori information will typically consist of terrain data, other important information about the tactical environment, intelligence about the opponent´s tactics, equipment and organization, known facts about the opponent´s logistics situation, as well as other kinds of tactical knowledge [Steinberg01]. Detailed geographical a priori information will be needed, in particular to support calculation of sensor-to-target detection, classification, and tracking parameters, spatial reasoning about target behaviour based on tactical doctrine, and real-time terrain-dependent management of sensor resources.

The FOI project *Information fusion in the command and control system of the future network-based defence* is developing a reusable information fusion demonstrator system. In the demonstrator, information will be transmitted from sensors to a Command and Control, *C2*, site. At the C2 site information will be fused and interpreted. Finally, the interpretations will be used to develop and issue control messages intended to improve sensor utilization in relation to predefined surveillance objectives, modeling a reactive *multisensor management* [Xiong02] concept. The paper describes this ongoing work that will integrate research results in the areas of force aggregation, ground tracking, and sensor management within a state-of-the-art scenario simulation environment. It presents arguments why scenario simulators are needed to provide early experience in integration, test, and demonstration of the many cooperating analysis methods and algorithms that will be needed in future high-level information fusion systems. Research results forming part of this effort are summarized.

2 Infofusion demonstrator 03 (IFD 03)

Our project aims to complete the development of a demonstrator system for tactical information fusion applied to simple ground warfare scenarios, and to perform a demonstration using this system in the Fall of 2003. The system will be called Infofusion demonstrator 03 (IFD 03). In the information fusion area there does not yet exist a scientific basis for the development of integrated systems which could be put to practical use after restructuring for robustness, security certification etc. Instead, the main purpose of the demonstrator project is to provide a research platform for experimentation with specific research issues, in particular the interplay between different modeling techniques used to address subtopics in this research area, as well as to create a means of spreading knowledge to interested parties about the current state of research in information fusion.

IFD 03 will integrate methods related to different fusion "levels" [Steinberg01], specifically multisensor-multitarget tracking, force aggregation, and multisensor management. It will exchange data in simulated real time in both directions between the scenario simulator and the fusion system. It will have three closely associated main capabilities: to provide a test bed for new methodology in information fusion, to provide a supporting scenario simulator for the generation of adequately realistic sensor and intelligence reports used as input to the fusion processes, and to offer general-purpose software tools,

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terrain models, and other prerequisites for visualization both of the development of the scenario over time and of selected characteristics and effects of the fusion processes.

Over the past few years FOI has acquired a simulation development platform, based on the commercial simulation framework Flames™ [Ternion03], suitable for test, experimental evaluation, evolutionary development, and demonstration of many kinds of event-driven scenario-based simulations. To adapt the Flames framework to the needs of information fusion research, advanced terrain modeling facilities were included [Hörling02], allowing fully integrated ("correlated") topographical and thematical models of geography to be used in the simulations. Recently, this platform was further extended by allowing program modules, developed using the problem-solving environment Matlab™ [MathWorks03], to be tightly integrated. Thus, the resulting development platform allows comprehensive reuse of commercially available software, as well as both program modules and scenario specifications previously developed by our own group or by other projects at FOI.

Key to achieving successful demonstrations will be appropriate visualization methods which can render concrete and tangible concepts like scenario, fusion node, sensor network, communication system, and doctrine. In future projects the demonstrator system may be extended with methods for the solution of new problems, such as generation and analysis of alternative forecasting and action options. The combined Flames-Matlab development environment should significantly facilitate the development and integration of such methods.

2.1 Why build an information fusion demonstrator?

While any scientific approach to understanding specific aspects of reality will have to be based on abstraction and isolation of each aspect considered, on the other hand, in the scenario-based forecasting models we want to build based on understanding obtained by reductionist approaches, all significant complexities of the real system need to be reflected. Thus, e. g., during the last half-century, weather forecasting has gradually developed, not primarily by discoveries of new, meteorologically significant physical phenomena, but by a combination of better mathematical models of the underlying physics, improved algorithms for their evaluation, improved data collection and exploitation in models, and last but not least, a gradually increased complexity and sophistication of integrative, scenario-based forecasting models, made possible by the exponential growth in computational capacity.

Granted that information fusion adds the serious complication of hidden, antagonistic human decision-making to the purely physical processes of weather forecasting models, the success of such modeling could anyway, we believe, provide some inspiration for information fusion research, although this research certainly has a long way to go before it can claim any comparable success [Hall01b]. So when will information fusion methodology have progressed sufficiently to make meaningful use of synthetic environment scenario simulators? Out of conviction that all necessary ingredients of complex forecasting models need to evolve together, we argue here that this is already the case.

The above-mentioned concept of reactive multisensor management requires that sensor control messages based on fusion results can be fed back to the sensors in (simulated) real time. This suggests an architecture where the entire multisensor data acquisition and fusion process is an integrated part of the scenario, in the guise of an acquisition management and information fusion function of a simulated C2 centre. Such an architecture is employed in IFD03.

We view the new demonstrator system as an extensible research and demonstration platform, where new methodological ideas can be realized, evaluated and demonstrated, and where various aspects of increasingly complex network-based information fusion systems can be tested in complex and reasonably realistic scenarios. Whereas our previous information fusion projects have focused on method and algorithm development for various specific problems, in particular clustering, aggregation, and classification of force units [Cantwell01] and sensor management [Xiong02], the development tools associated with the new platform are intended to support substantial reuse, including evolutionary extension and rewrite, of both software and simulation scenario descriptions [Hörling02].

2.2 Research goals and issues

In line with recent meta-models of multisensor-multitarget fusion [Mahler00], we view Level 2 information fusion [Hall01] as the interpretation of a flow of observations in terms of a model of a physical process in space and time. This process describes the stochastic interaction between an observation system, a complex target system (such as a hierarchically organized enemy unit) and a complex environment. According to this view, what distinguishes Level 2 from Level 1 fusion is mainly the much higher complexity of the target and environment models, involving imperfectly known doctrines which influence the behaviour of the target system in a way that needs to be stochastically modeled.

The purpose of the interpretation process is partly to estimate current and near-future values of a set of possibly unobserved behavioural parameters of the target system,

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partly to improve the estimates of measured parameter values. In IFD 03, no attempt is made to estimate other doctrinal parameters than force structure. In the not too distant future, however, it may become feasible to estimate a larger set of behavioural parameters, such as for example, our belief in the proposition "the enemy is aware he has been detected".

In information fusion applications based on complex ground scenarios involving interaction between several, partially antagonistic complex systems, scenario-based simulation is often the only methodology available for systematic characterization and analysis of system behaviour. This methodology permits *experimentation* according to a top-down approach with various methods, configurations, and parameter values, *evaluation* of the effectiveness and efficiency of algorithms and modeling methods in relation to a reasonably realistic approximation of the final application environment, as well as *verification* that all problem-relevant components have been included and modelled on an adequate level of resolution. Also, it supports the establishing of a *balanced system design*, by allowing the discovery and early elimination of vague concepts and unsolved or inadequately treated subproblems, as well as system performance bottlenecks. Design proposals which do not work even in a simplified synthetic environment can be identified and quickly eliminated, while methods which seem to be promising can be selected for a deeper analysis.

The IFD 03 project rests on a small number of basic methodology principles, i.e., cooperation between methods on fusion levels 1, 2, and 4, a tight coupling between a qualified synthetic environment and models of sensor behaviour, target force behaviour, and communication, and, last but not least, exploitation of current convergence trends between methodologies on fusion levels 1 and 2. This perceived convergence consists of a combination of finite set statistics [Mahler00], Dempster-Shafer clustering [Schubert02, Schubert02], and particle filtering [Arulampalam02]. We believe that a combination of these techniques may eventually permit concurrent tracking of both solid objects (e.g., vehicles) and group objects (e.g., ground force units), logically connected via uncertain and vague information in the shape of doctrinal rules and communication capability.

Thus, the project focuses on analysis, evaluation, and presentation of new methodology for a collection of important subproblems in automatic information fusion, i.e., ground target and group target tracking, force aggregation, multisensor management, and short term situation prediction.

Successively for various scenarios, in the future we also expect to create by this approach the capability to address various effectiveness issues, which might be generically described as:

- what improvement in effectiveness (measured, perhaps, as increased information quality [Arnborg00], or information gain [Xiong02]) of various aspects of situation modeling can be expected from specified information fusion methods?

- what improvement in effectiveness can be expected from a network-based defence technology, with and without information fusion methods?

- how does delays and "inertia" of various kinds, arising from, e.g., information transmission or information processing, influence expected improvements in effectiveness?

2.3 Conceptual description

The first demonstration event is currently thought to consist of a 20-30 minute replay session, corresponding to 2-4 hours of real time. This scenario development will be prerecorded during possibly several hours of simulator runtime. Surveillance information is generated during the simulation by a set of sensor models, dynamically instantiated as a collection of distributed actors interacting with their scenario environment. The sensors deliver reports more or less continuously to a fusion node, symbolizing a future division-level intelligence staff.

The planned demonstrator can be described as an executable model of a two-party game between a multi-target [Mahler00] and a fusion node. Technically, services are implemented as "cognitive models", i.e., behavioural submodels of simulated actor models. According to Flames conventions, models should be written in C or C++. Since complex fusion algorithms are in general more conveniently developed using a high level problem solving environment such as Matlab, we devised a process by which Matlab models can be fully integrated with the Flames system. This process is based on automatic translation of Matlab modules into C using the so-called *Matlab C++ Compiler*. The resulting modules are compiled, then linked with other user-developed code originally written in C, C++, and/or Matlab, and with the Flames scenario execution system. Procedure calls can be made in both directions between code originally developed in Matlab and C/C++. Thus, a tight coupling has been established between Flames and Matlab which is exploited, e.g., to provide tracking algorithms with terrain model data from Flames, as well as to provide particle clouds and other estimates of target positions for visualization on top of a map background. Both services were originally written in Matlab.

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The primary types of objects to be involved in our first simulation use-case (described in section 2.4) will be:

- "red" (enemy) *forces of batallion strength*, consisting of several mechanized and armoured subunits,

- "blue" (own) *division-level intelligence staff* (fusion node), which can automatically and almost instantly communicate digital information with the following reconnaissance resources:

- blue *home guard soldiers* who observe the enemy advance using binoculars and possibly other devices,

- blue *surveillance UAVs* controlled by radio from the fusion node, carrying video or IR cameras, SAR radar or laser radar, or some combination of such sensors,

- blue *communications intelligence (COMINT) surveillance units* which can measure bearings to radio transmitters and analyze radio signals (but not decode their messages). They communicate measured directions and signaling timings to the fusion node,

- blue *ground target multisensor systems* capable of detecting acoustic or seismic vibrations, as well as quasistatic electromagnetic fields ("metal detectors"). From these detections, target type and sometimes identity may be concluded, at least under favourable environmental conditions.

Red and blue ground units move largely according to doctrinal rules on or near roads. Their speed and movement pattern is influenced also by road and terrain trafficability, varying between vehicle and unit types. Blue UAVs fly according to a simple dynamic model, while immediately obeying control messages from the fusion node. The control messages are generated by the fusion service *sensor-control-UAV*. The fusion node uses the sensor information as input to aggregation, tracking, quality assurance, and sensor management processes (see section 3.1.5) to achieve the best possible situation characterization, given the modelling constraints inherent in the demonstrator system.

2.4 Scenario

The scenario is imagined to take place in May 2015. Tension in the Baltic Sea area has grown gradually over several years and the state of alert of the Swedish defence has been raised. At the outbreak of the war a number of concurrent events occur. Of these, a "trojan horse" enemy landing at the ferry harbour at Kapellskär is judged to constitute the greatest threat. If the enemy is allowed to move further inland towards the town of Norrtälje and occupy the lake passes there, he will be difficult to defeat with available own resources.

When the defending batallion commander has received his action orders he wants to obtain as fast as possible a detailed picture of the enemy's size, composition, and activity in order to be able to judge the enemy's action options and decide his own. The only intelligence sources available at the time of the landing are four Home Guard patrols deployed at strategic points along the enemy advance routes, Figure 2.1. The battalion's UAV group is ordered to immediately direct two UAVs for reconnaissance above Rådmansö, to obtain as quickly as possible a more detailed picture of the enemy situation. Figure 2.2 shows the situation at 18.45. The two UAVs directed to Rådmansö have by then delivered a number of reports which have contributed to the rather detailed situation picture. The chief intelligence officer is able to state that the enemy force consists of a mechanized batallion reinforced by antiaircraft and artillery units, advancing along two roads towards Norrtälje. However, since the bridge across Åkeröfjärden was demolished by the Home Guard at 18.30, the enemy advance along the main road has been decisively delayed.

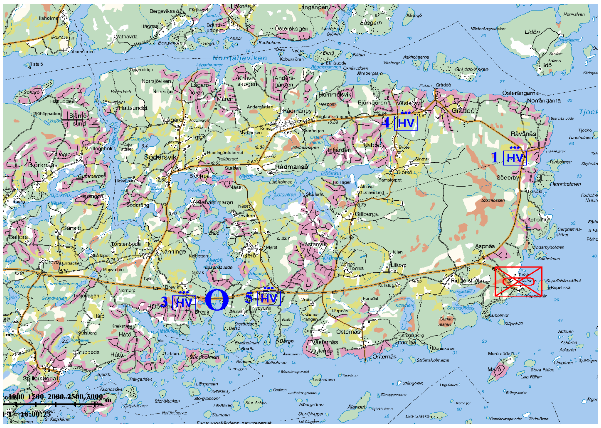

Figure 2.1 Information collection situation at Rådmansö 18.00. Four Home Guard (HV) patrols are located at critical points along the enemy's approach route.

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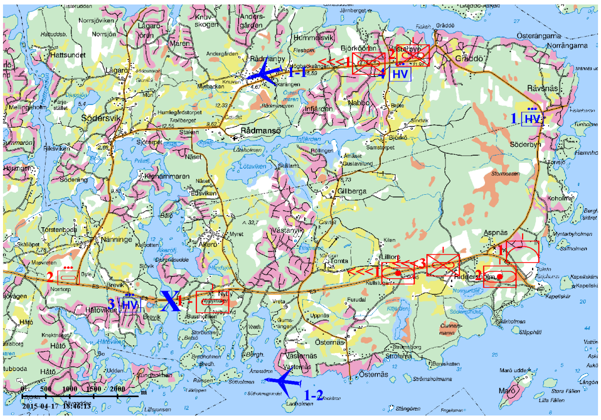

Figure 2.2 Situation picture at 18.45.

3 Architecture of IFD 03

Based on a commercial simulation framework, IFD03 will offer its users a standard procedure for scenario definition, which can be used to combine in various ways the different object models mentioned in section 2.3, to form specific scenarios. Models and methods are not allowed to require any operator interaction during the course of the simulation. Through a closed feedback loop, the sensor management algorithms in the demonstrator control position, movement, attitude and other parameters for a subset of the sensors which participate in the scenario.

3.1 Object models and cognitive models

3.1.1 Target object models

The enemy batallion model consists of slightly more than 60 vehicles: battle tanks, armed personnel carriers, antiaircraft missile launch vehicles, grenade launcher vehicles, and two types of truck. To create models for these target objects, a table of normalized detection, classification, and identification probabilities for different aspect angles, assuming fixed target distance, is needed for each type of sensor. In these tables, objects are assumed to be viewed at different angles against a clutter-free background. Properties of the environment, in particular ground properties at the location of the object and relevant features along the line of sight (atmosphere, vegetation) will then reduce these probabilities.

For ground sensors, data are needed on the acoustic and seismic vibrational signal strength that each type of vehicle generates, as well as on the electromagnetic field signal strength for magnetic sensors. The direction of movement of the vehicle can be disregarded, however, its speed and associated throttle level should be taken into account, since they influence the generation of vibrations. The speed of the object also affects the detection probability of GMTI and SAR radar sensors. Using IR sensors, in addition to warm or hot surfaces of the vehicles themselves, hot exhaust gases, still warm wheel or track depressions in the ground might be detected.

3.1.2 Organisation, motion and communication models of "red" forces

This model [Caidahl03], Figure 3.1, describes the behaviour and motion of enemy ground forces according to their doctrine (i.e., the set of tactical rules that is expected to guide the behaviour of the opponent's army). This includes telecommunication and transportation along a road network of mechanized forces in hostile territory. Ground force objects, which consist of behaviourally connected object models, are able to move autonomously along the road network, guided by a limited number of parameters, including formation, destination, starting time, marching speed, and preferred roads. A force unit can march in formation, make route choices autonomously or according to prespecified instructions by the user, avoid obstacles by changing route, detect enemies, and replace lost commanders. Using Dijkstra's shortest route algorithm, the model calculates those parts of the route which were not prespecified by the user.

3.1.3 Sensor modeling principles

Below, we discuss general properties which environment and sensor models should possess to enable sensor models to provide relevant information. Detailed descriptions of sensor models are outside the scope of this paper but can be found in the sensor literature.

How a sensor can be modelled depends strongly on the sensor type. In general what is needed is some kind of detection or recognition time for each sensor, i.e., a shortest time during which an object must be continuously visible by a sensor to be detected, classified, or identified, each step in this sequence requiring additional time.These times depend on sensor type, obstacles in the line of sight, and target object type, in combination with target attitude in relation to the sensor.

Vital for an image-generating sensor's ability to detect, classify, and identify a target is the number of pixels in the sensor's image plane spanned by the target, i.e., the resolution of the sensor. This depends on optics, zoom factor etc. In addition, the contrast between light and dark parts of the image has to be strong enough [Klein97]. Also, the object's aspect angles in relation to the observing sensor are of relevance. Finally, the surrounding environment generates clutter which reduces the sensor's ability to distinguish objects against the background pattern.

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Vegetation can conceal all or parts of the target. There is always a risk of false detection by a sensor. Sensors used to detect ground targets will likely show a greater rate of false detection the more difficult prevailing surveillance conditions are, i.e., the more hilly and diversified the terrain is, and the more complex sound and seismic wave transmission conditions are.

3.1.4 Sensor carriers (platforms)

Sensors will usually be carried by some kind of platform, ranging from aircraft or UAVs to APCs, soldiers and civilians. They can be characterized by their ability to elevate their sensors to different heights above ground or sea, speed, ability to move to various positions after longer or shorter alerting time, etc. On the ground stationary

Figure 3.1 Snapshot from a simulation of enemy troop movement at Rådmansö

platform systems may exist, which are either completely immobile, or are able to move only after a certain redeployment time. Vehicle-bound sensor systems may also be present, whose carriers are either restricted to move on roads of some minimum quality, or are able to move in terrain of some minimum trafficability. A human can move slowly by foot even in difficult terrain, faster in better terrain, and can accompany vehicles. Need for cover while moving reduces the choice of routes. Requirements on geography for each type of platform to be able to deploy and to achieve a given maximum speed of movement need to be modelled. The minimum time to get in motion after a redeployment order is given, and to start measurements after a deployment spot has been reached also needs to be specified or modeled.

3.1.5 Cognitive model of the fusion node

The fusion node has access to a priori information in the form of an advanced terrain model and a doctrine and materiel database, generically describing the enemy military organization. Also, it has the capability to perform dynamic remote control of a multisensor which can observe portions of this force. On the highest level of abstraction the fusion node provides services for report clustering, aggregation, classification, and tracking of force units, and allocation and control of information collection resources, see below. When the fusion node has received a sufficient amount of credible sensor reports, it calls the *force aggregation service*, a component of the cognitive model of the fusion node. This service generates aggregation results based on available sensor, terrain, and doctrinal information. It is capable of "recursively" aggregating lower units to higher when adequate information is present. When the fusion node has created an aggregation result, this is delivered to the *particle filter (pf) tracking service* to perform *force unit*, or *group*, tracking. Each timestep, this service delivers to the fusion node quality certified information about the system state of every tracked unit. The pf tracker service is employed by the *multisensor management service* to allocate, move, and direct available sensor resources in order to satisfy a situation-dependent optimization criterion based on the concept of *information gain* [Xiong02]. A *quality assurance* (*QA*) *service* connected to the group tracker continuously compares the results from trackers on different aggregation levels and raises an alarm when a prespecified information quality tolerance is violated. This signal will then influence the sensor resource allocation algorithm in order that adequate sensor resources are allocated to the failing tracking task, to satisfy if possible the prespecified quality tolerance.

3.2 Methods and algorithms in the fusion node

3.2.1 Methods for tracking of force units and short-term prediction of their parameters

The development of methods for information fusion assumes the availability of effective multisensor fusion methods. In our demonstrator a new method for tracking of ground vehicles, based on particle filtering, will be included [Sidenbladh03a, Sidenbladh03b]. Since multitarget tracking is typically a non-linear, non-gaussian

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problem, in particular in the ground target case, one might expect particle filtering to be superior to Kalman filtering in most of these applications. Also, methods for multisensor-multitarget fusion are beginning to appear, which seem to allow the creation of useful mathematical

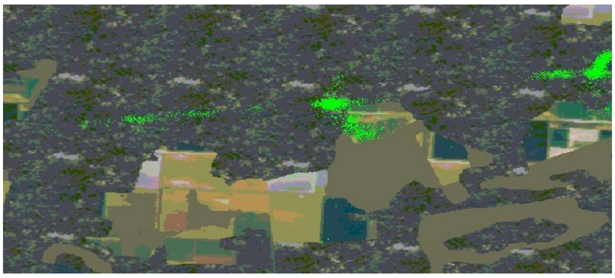

Figure 3.2 Using a first version particle filter ground target tracker in the Rådmansö scenario.

models and algorithms for *detection*, *tracking*, and *classification* of *group targets*.

3.2.2 Template-based methods for force identification and aggregation

The aggregation problem for sets of objects has some similarities with the classification and identification problems for single objects. From observations of a few objects, or more specifically, of certain attributes of a few objects, the task is to find out which type(s) of aggregate (e.g., force unit) the objects belong to. A large force can be dispersed over a large area, so that two observations at two different locations may refer to the same unit. This creates difficulties already when the observations are concurrent. If they are not, a correlation problem has to be addressed as well. In ground target tracking, due to limited visibility and the attendant difficulty to track each member of a set of objects accurately over time, correlation should focus on aggregates (force units), which are the primary objects of interest, rather than on single solid objects such as vehicles. Thus, aggregation and correlation are not independent but need to be addressed together.

In the aggregation problem one wants to compare what has been observed with prior knowledge, in order to classify the observed phenomenon [Cantwell01]. This is usually achieved by creating a model of each relevant unit based on doctrinal knowledge, against which observations are compared. The more detailed knowledge one has about relevant units, the more detailed models can be created, improving the opportunities to decide from which unit type an observation originates.

A new methodology for clustering intelligence reports exploits both "attracting" and "conflicting" information to form a measure of the support for the proposition of considering two reports as relating to the same event [Schubert02, Schubert03]. For example, attracting information from communications intelligence may support the hypothesis that two communicating objects belong to the same unit (on some level), while other conflicting sensor information indicating great geographical distance might contradict the hypothesis that the two objects belong to the same platoon. This method will be used in the force aggregation module of the demonstrator.

3.2.3 Resource allocation and multisensor management

Starting from an assumption about which information is to be collected, when and where it should be collected, and when it is needed, available sensor resources are to be assigned [Xiong02]. Basically, the purpose of multi-sensor management is to make suitable sensors deliver appropriate information about all relevant objects at the proper time. A network-based defence will require autonomous, intelligent sensor fusion nodes. These must be able to request information from the network, as well as offer their own information services. The autonomy offered to the nodes also requires them to be able to coordinate their activity. We are studying how game-theoretic negotiation may be used to achieve effective coordination of static and mobile sensors [Johansson03, Xiong03].

A sensor resource management method being developed for the demonstrator deals with the following problem: a user ("decision maker") is given information about the position of various objects over time by means of a target tracking system. The decision maker is interested in where the objects are heading and may ask the system at any time which support there is for the hypothesis that some object will pass one or more specified road sections or terrain passes. In the problem it is assumed that the sensors which feed the tracking have limited range and are limited in number. The system may therefore have to move sensors to provide the best possible answers to the decision maker's queries. To reduce the search space of this task we employ ANTS simulation [Svenson03] to map out likely avenues of approach of the enemy.

4 Conclusion

The paper describes an ongoing effort to build an information fusion demonstrator system where new ideas in situation and process refinement [Steinberg01] may be tested and demonstrated. The motives behind this project, its system architecture and development process, and some of the fusion methods being developed for the system were briefly described. Whereas building such a system merely for the purpose of performing a few demonstrations in front of an audience could well be considered economically extravagant, we believe that by

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basing its design on an extensible, well-established software development framework, we have created a problem solving environment capable of effectively supporting our information fusion research for years to come.

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